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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(84)90443-X

THE ROLE OF SEQUENTIAL TRANSFER IN UNNATURAL-PARITY TRANSITIONS IN THE ^{208}Pb(p, t)^{206}Pb REACTION ☆

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Received 10 October 1983

Angular distributions have been obtained for several unnatural-parity transitions in the ^{208}Pb(p, t)^{206}Pb reaction at E_p = 20.0 and 50.5 MeV. It is found that the sequential (p, d) (d, t) process provides an adequate description of these transitions at both energies.

The importance of sequential transfer in the description of (p, t) or (t, p) reactions is still in discussion (see ref. [1]). In natural-parity transitions it is difficult to study the sequential-transfer process because it interferes with the direct process of which in general the enhancement factors are not sufficiently known. On the other hand, unnatural-parity transitions in such reactions are well suited to study the two-step mechanism since the direct transition is almost completely forbidden. This is due to the fact that the ground-state of the triton is mostly (90%) a totally spatial-symmetric S-state, which results in the total transferred angular momentum being equal to the orbital angular momentum of the neutron pair (2). Therefore direct unnatural-parity transitions are only possible via the small S′- and D-components of the triton wave function.

In order to study the reaction mechanism of unnatural-parity transitions, the transition to the 3^+ state at 1.34 MeV in the ^{208}Pb(p, t)^{206}Pb reaction has been investigated by several groups [3–8]. This state is well suited for this purpose because its wavefunction is simple [9] and because other two-step effects like inelas-excitation combined with direct transfer can be neglected. De Takacsy [3] and Charlton [4] reported that the sequential-transfer process could fully account for the shape and absolute cross section of this transition measured at 35 MeV [5]. On the other hand, Nagarajan et al. [6] obtained also a good description of the same data for a direct transition calculated with exact finite-range and a realistic triton wave function (including the S′- and D-components). However, a rather large value of the radius for the neutron bound-state wave function was employed in this calculation. Exact finite-range calculations for both direct and sequential transfer have been performed by Igarashi and Kubo [7] also with a realistic triton wave function. Here it turned out that the amplitude of the direct process was about ten times smaller than that of the sequential process. In similar calculations at 22 MeV (ref. [7]) the direct transfer amplitude turned out to be even smaller, compared to the sequential transfer, which itself gave a good description of the shape and magnitude of the measured angular distribution [8].

In order to solve the problem of different interpretations of the reaction mechanism in such unnatural-par-

☆ This work was part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM) which is financially supported by the Nederlandse Organisatie voor Zuiver-Wetenschappelijk Onderzoek (ZWO).

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ity transitions, one should study more cases and for a wider range of bombarding energies. We choose also the ^{208}Pb(p, t)^{206}Pb reaction, because, apart from the 3_1^+ state at 1.340 MeV, several other unnatural-parity states of simple character exist in ^{206}Pb. Data were obtained at energies of 50 and 20 MeV for several of these states, most of which had not been observed in earlier studies, because the cross sections are very small and a rather high resolution is required to separate the states of interest from neighbouring ones.

The 50 MeV data were obtained at KVI, Groningen. A self-supporting target approximately 1 mg/cm^2 thick was bombarded with an analyzed beam of 50.5 MeV protons from the KVI variable-energy cyclotron. The outgoing tritons were momentum analyzed with a QMG/2 magnetic spectrograph and detected with a position-sensitive proportional detector in the focal plane. Cross sections of levels up to 3.5 MeV were measured from θ = 4.5° to 50° in steps of 2°–3°. The overall energy resolution was between 25 and 30 keV, which was sufficient to observe the weakly excited unnatural-parity states at 1.340 MeV (3^+), 2.384 MeV (6^-), 2.939 MeV (6^-) and 3.122 MeV (3^+). The data are shown in fig. 1. The 20 MeV experiment was performed with the AVF cyclotron of the Free University, Amsterdam. The thickness of the ^{208}Pb target was 500 μg/cm^2. The tritons were detected by an array of position–sensitive solid-state detectors placed in the focal plane of an Enge split-pole spectrograph. An energy resolution of 15–18 keV was obtained. Five unnattural-parity states have been observed at 1.340 MeV (3^+), 1.703 MeV (1^+), 2.384 MeV (6^-), 2.826 MeV (4^-) and 3.122 MeV (3^+); these data are shown in fig. 2. The 1^+ state was 1.703 MeV could only be resolved at forward angles from the strongly excited 4^+ state at 1.68 MeV.

The sequential-transfer calculations were performed with the zero-range coupled reaction channels (CRC code CHUCK. Finite-range effects in the sequential transfer are assumed to be small for unnatural-parity transitions because they can be expressed in terms of a direct step mechanism [10]. For the same reason also non-orthogonality effects, which arise from the use of the prior–prior form of the sequential-transfer amplitude in the calculations, are expected to be small. The sequential-transfer calculation has no free parameters: the choice of the optical potentials and single-nucleon transfer strengths can all be checked against the elastic

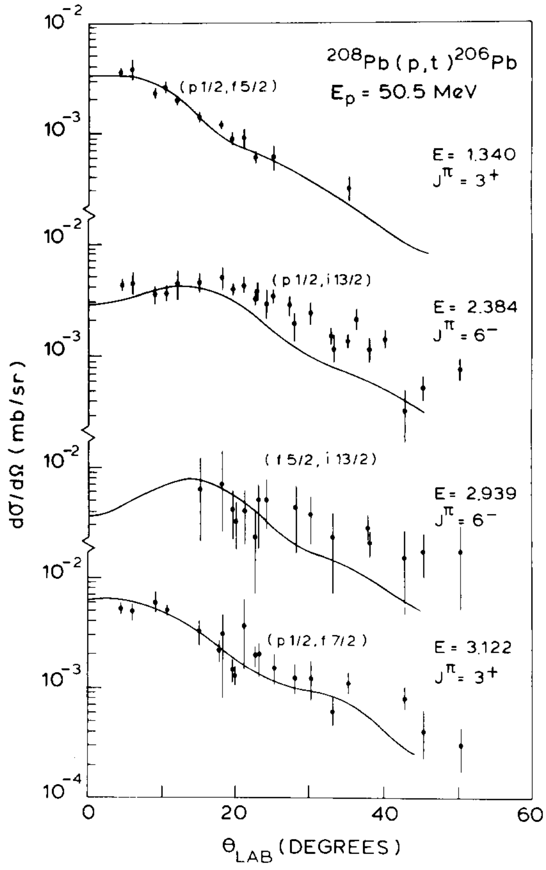

Fig. 1. Measured and calculated angular distributions for the ^{208}Pb(p, t)^{206}Pb reaction at E_p = 50.5 MeV.

scattering and the (p, d) and (d, t) reaction data. The parameters are given in table 1. The ones used for our calculations at 50 MeV reproduced the data of the ^{208}Pb(p, d) reaction at 55 MeV [12] and the ^{208}Pb(d, t) reaction at 50 MeV [13]. With the 20 MeV set the data of the ^{208}Pb(p, d) reaction at 20 MeV [14] and the ^{208}Pb(d, t) reaction at 17 MeV [15] were also well described. Calculations by True and Ford and also by Hengeveld and Allaart [9] show that the wave functions of the unnatural-parity states consist all for nearly 100% of one two neutron–hole configuration. These configurations are indicated in the figures. The spectroscopic amplitudes to be used in the CRC-calculations for a final state with a pure configuration $(j_1^{-1}, j_2^{-1})_J$ and intermediate state with

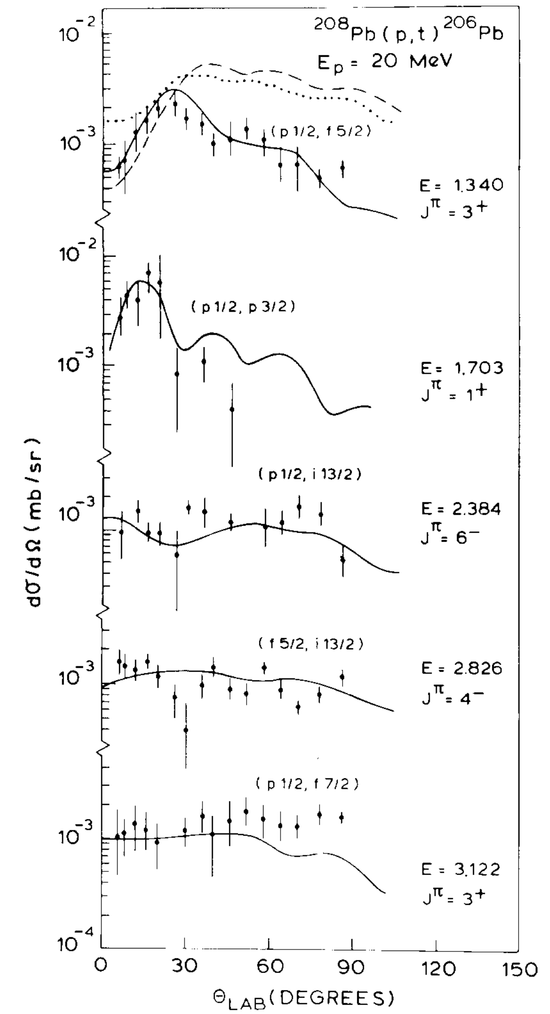

Fig. 2. Measured and calculated angular distributions for the ^{208}Pb(p, t)^{206}Pb reaction at E_p = 20.0 MeV. The dotted line corresponds to the $(p_{1/2}, f_{5/2})$, the dashed to the $(f_{5/2}, p_{1/2})$ sequential transfer path.

spin j, are given by the following expressions [17]:

$$S_{\mathrm{pd}}^{1/2}(0^+ \to j^{-1}) = (2j+1)^{1/2} V_j ,$$

$$S_{\mathrm{dt}}^{1/2}(j^{-1} \to (j_1^{-1}, j_2^{-1})_J) = (2j_2+1)^{-1/2}$$

$$\times (2J+1)^{1/2} V_{j_1} \delta_{j, j_2}$$

$$- (2j_1+1)^{-1/2} (2J+1)^{1/2} V_{j_2} (-)^{j_1+j_2-J} \delta_{j, j_1} ,$$

where V_j^2 is the occupation probability of the orbit with spin j.

Table 1
Optical-model parameters and transfer strengths used in the calculations. D_0(p, d) = 122.5 MeV fm$^{3/2}$; D_0(d, t) = 182.0 MeV fm$^{3/2}$.

Energy (MeV)	Projectile	V_I (MeV)	r (fm)	a (fm)	W_v (MeV)	$4W_D$ (MeV)	r_I (fm)	a_I (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_c (fm)
20	p	−57.6	1.17	0.75	−2.1	−35.2	1.32	0.66	6.2	1.01	0.75	1.25 a)
	d	−110.4	1.17	0.79	−0.3	−78.9	1.29	0.62	6.0	1.12	0.47	1.25 a)
	t	−168.9	1.2	0.65	−9.9	–	1.6	0.97	6.0	1.15	0.92	1.2 b)
	n	–	1.25	0.65	–	–	–	–	λ = 25.0			
50.5	p	−47.52	1.168	0.81	−4.09	−22.0	1.23	0.777	5.93	1.13	0.79	1.18 c)
	d	−101.5	1.17	0.79	−6.6	−47.2	1.29	0.62	6.0	1.12	0.67	1.3 a)
	t	−160.0	1.25	0.72	−20.0	–	1.45	0.72	–	–	–	1.4 d)
	n	–	1.25	0.65	–	–	–	–	λ = 25.0			

a) Ref. [11]. b) Ref. [8]. c) Result of a fit to the 50.5 MeV elastic scattering data. d) Determined for 40 MeV ^{3}He on ^{208}Pb (ref. [16]).

The results of the CRC-calculations at 50.5 MeV are shown in fig. 1 together with the experimental data. In all four cases the calculations give a good description of the shape of the angular distributions. The absolute cross sections of the 3^+ state at 1.340 MeV and the 6^- state at 2.384 MeV are well predicted by the calculations. The calculations for the 6^- state at 2.939 MeV and the 3^+ state at 3.122 MeV had to be multiplied by factors of 2.0 and 1.6, respectively.

In fig. 2 the 20 MeV data for the unnatural-parity transitions are shown together with the results of the CRC-calculations. For the 3^+ level at 1.340 MeV also the curves are shown that correspond to the sequential paths: $(p_{1/2}, f_{5/2})$ and $(f_{5/2}, p_{1/2})$ separately. It is seen that the two paths interfere destructively, resulting in an angular distribution that is quite different from the ones corresponding to the separate paths, but in very good agreement with the experimental data. This supports the idea that the excitation of this state is predominantly due to sequential transfer. As mentioned earlier for the 1^+ level at 1.703 MeV only the data points at forward angles could be determined. The CRC-calculations give a nice description of the data. The calculated angular distributions of the 6^- level at 2.384 MeV and the 4^- level at 2.826 MeV were multiplied by 1.5 and 2.0, respectively. The data for the 3^+ level at 3.122 MeV were well described again.

The above results show that the angular distributions, measured at two widely different bombarding energies, for a variety of unnatural-parity states in the ^{208}Pb(p, t)^{206}Pb reaction, can be consistently described both in shape and magnitude (normalization factors needed are unity or close to unity) by (p, d) (d, t) calculations. From this we conclude that sequential transfer is the dominant reaction mechanism for the transition to such unnatural-parity states. Possible contributions from a direct transition due to the small S′- and D-components in the triton wavefunction or from intermediate continuum states in the sequential transfer still have to be investigated.

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